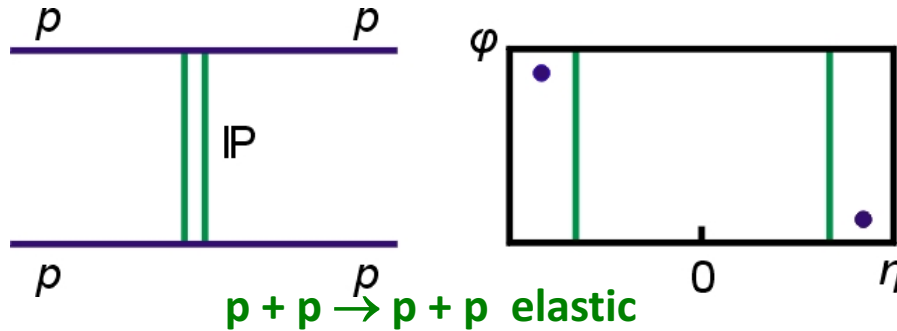


Roman Pots at RHIC

Włodek Guryn

1. PP2PP Experiment – pp elastic scattering
2. Roman Pots at STAR – physics with tagged forward protons

Proton – Proton Elastic Scattering



four-momentum transfer squared: $t = (p_1 - p_3)^2 \approx p^2 \theta^2$

$$\frac{d\sigma}{dt} = \pi |f_c + f_h|^2$$

$$f_h = \left(\frac{\sigma_{tot}}{4\pi} \right) (\rho + i) e^{-\frac{1}{2} B |t|}$$

$$f_c = -\frac{2\alpha G_E^2(t)}{|t|} e^{i\alpha\phi}$$

$$\rho = \left. \frac{\text{Re } f_h}{\text{Im } f_h} \right|_{t=0}$$

$$\sigma_{tot}^2 = \left(\frac{16\pi (\hbar c)^2}{1 + \rho^2} \right) \left. \frac{d\sigma_{el}^h}{dt} \right|_{t=0}$$

Status in 1990: ρ – measurement at $\text{Sp}\bar{\text{p}}\text{S}$

It was summer of 1990 or so when I attended a student/postdoc seminar at FNAL (I was working on D0 experiment at the time). I learned about the anomalous ρ measurement at CERN.

Volume 198, number 4

PHYSICS LETTERS B

THE REAL PART OF THE PROTON-ANTIPROTON ELASTIC SCATTERING AMPLITUDE AT THE CENTRE OF MASS ENERGY OF 546 GeV

UA4 Collaboration

Amsterdam–CERN–Genova–Napoli–Palaiseau–Pisa

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P KLUIT ¹, S LANZANO ^d, G MATTHIAE ^{d 3}, L MEROLA ^d, M. NAPOLITANO ^d,
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G SETTE ^b, J. TIMMERMANS ¹, C VANNINI ^c, J VELASCO ^{a 5}, P G VERDINI ^c and F VISCO ^d

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Received 25 August 1987

Proton–antiproton elastic scattering was measured at the CERN SPS Collider at the centre-of-mass energy $\sqrt{s} = 546$ GeV in the Coulomb interference region. The data provide information on the phase of the hadronic amplitude in the forward direction. The conventional analysis gives for the ratio ρ of the real to the imaginary part of the hadronic amplitude the result $\rho = 0.24 \pm 0.04$.

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PHYSICS LETTERS

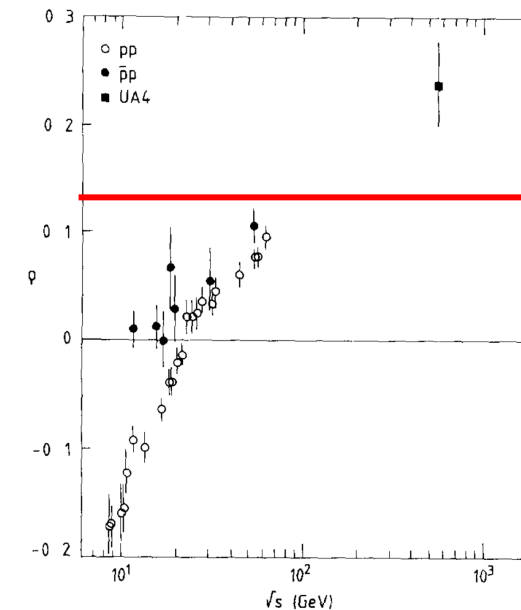


Fig. 4 The present result on the parameter ρ is shown together with lower energy data for pp and $\bar{\text{p}}\text{p}$ elastic scattering

The expected value was $\rho = 0.12$

Knowing that RHIC program was being formulated I decided that this would be a good thing to check at RHIC.

The Gap – Status at the time of the proposal

Highest energy at that time:

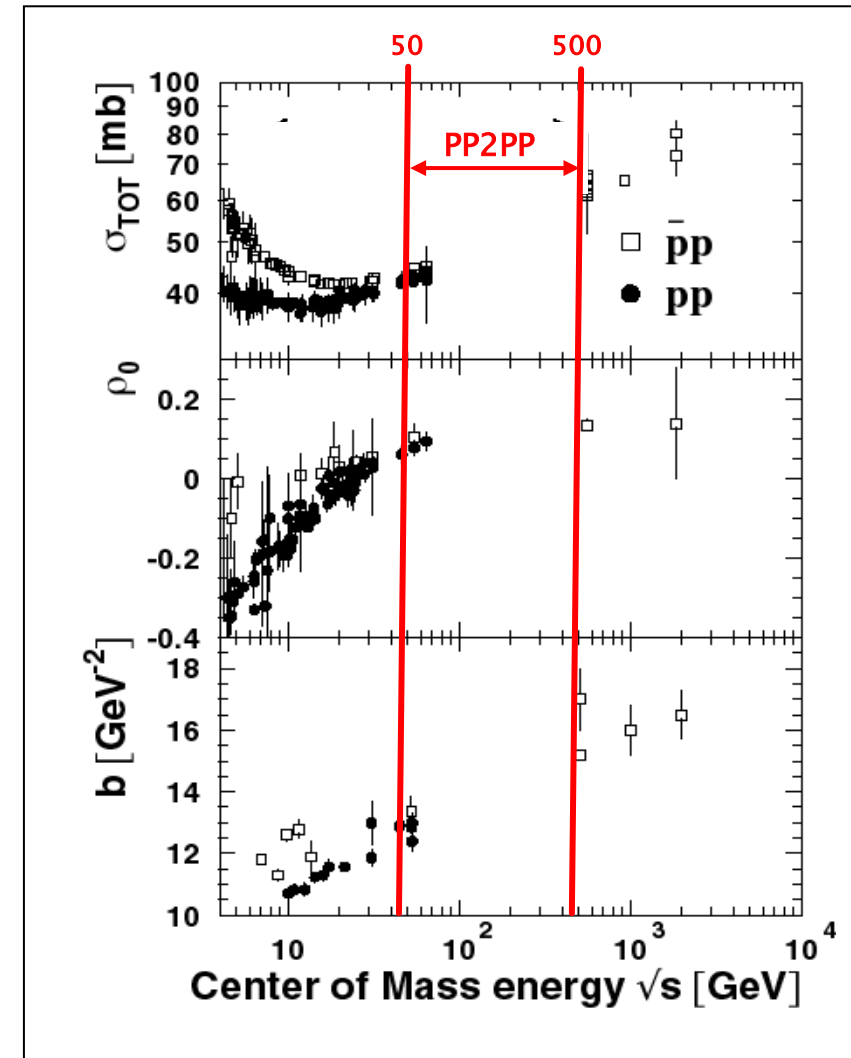
pp: 63 GeV (ISR)

$p\bar{p}$: 1.8 TeV (Tevatron)

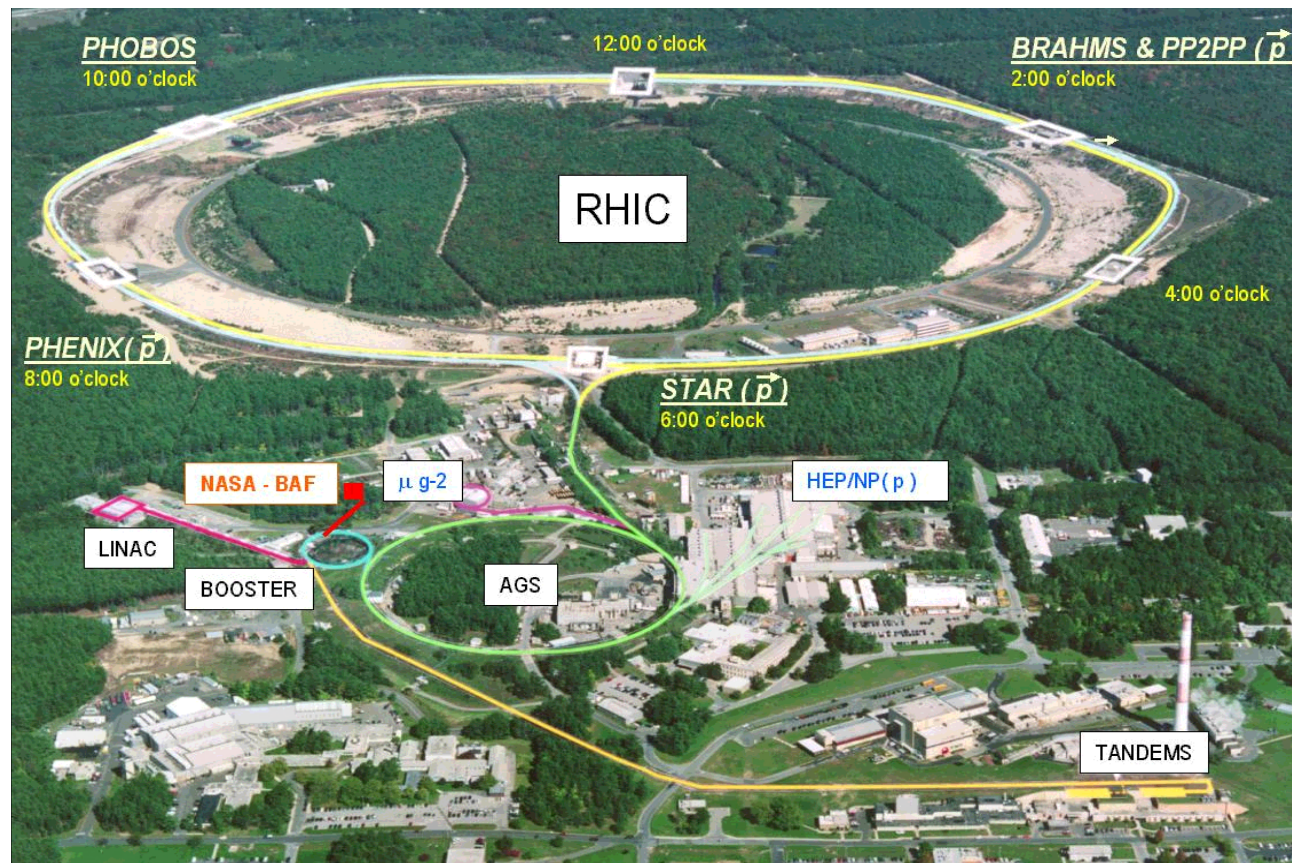
pp2pp energy range:

$50 \text{ GeV} \leq \sqrt{s} \leq 500 \text{ GeV}$

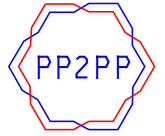
$$\rho = \frac{\text{Re } f_h}{\text{Im } f_h} \Big|_{t=0}$$
$$\sigma_{tot}^2 = \left(\frac{16\pi (\hbar c)^2}{1 + \rho^2} \right) \frac{d\sigma_{el}^h}{dt} \Big|_{t=0}$$
$$f_h = \left(\frac{\sigma_{tot}}{4\pi} \right) (\rho + i) e^{-\frac{1}{2}B|t|}$$



A trivia question: How many experiments at the beginning of RHIC?



The Collaboration: LOI #1 at RHIC



TOTAL and ELASTIC pp CROSS SECTIONS AT RHIC

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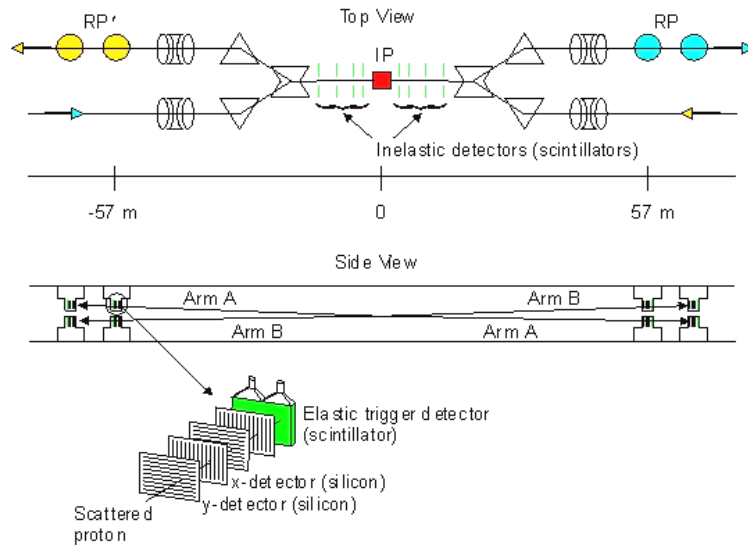
Abstract

We are proposing to study proton-proton (pp) elastic scattering at $\sqrt{s} = 500$ GeV. The lattice configuration and the angular coverage of the detector will allow the simultaneous study of all three regions that characterize elastic scattering, namely the Coulomb dominated region, the Coulomb-hadronic interference region and the hadronic dominated region, for four momentum transfer t in the range $0.0005 < t < 0.12 \text{ GeV}^2/c^2$. The case for the large t up to $6 \text{ GeV}^2/c^2$ is also presented. Application to the case of polarized beams is also discussed.



- We had very smart and competent people who were attracted to a small experiment at a world class facility – this was crucial.
- We were also lucky to get support from many people not on PP2PP but who were interested enough to find time to solve many technical issues and participate in construction – also very crucial.
- They were STAR collaborators at the time (Dave Lynn, Tonko Ljubicic, Jeff Landgraf, Bob Soja), also from BRAHMS (Bob Scheetz, John Hammond) and PHENIX (Steve Booze) and many at C-AD.

Principle of the Measurement of the Forward Protons



- Forward protons have very small scattering angles θ^* , hence beam transport magnets determine their trajectory.
- The optimal position for the detectors is where scattered protons are well separated from beam protons.
- Need Roman Pot to measure scattered protons close to the beam without breaking accelerator vacuum.

The relation of the position, angle, and dispersion of the beam particle at points s_2 and s_1 with respect to reference orbit is described by the transfer matrix

$$\begin{pmatrix} x(s_2) \\ x'(s_2) \\ y(s_2) \\ y'(s_2) \\ \Delta p/p \end{pmatrix} = \begin{pmatrix} v_x & L_x & m_{13} & m_{14} & D_x \\ v'_x & L'_x & m_{23} & m_{24} & D'_x \\ m_{31} & m_{32} & v_y & L_y & D_y \\ m_{41} & m_{42} & v'_y & L'_y & D'_y \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x(s_1) \\ x'(s_1) \\ y(s_1) \\ y'(s_1) \\ \Delta p/p \end{pmatrix}$$

Principle of the Measurement

Beam transport equations for elastically scattered protons: **relate measured position at the detector to scattering angle at the IP (beam dispersion can be neglected).**

$$\begin{pmatrix} x_D \\ \Theta_D^x \\ y_D \\ \Theta_D^y \end{pmatrix} = \begin{pmatrix} a_{11} & L_{eff}^x & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & L_{eff}^y \\ a_{41} & a_{42} & a_{43} & a_{44} \end{pmatrix} \begin{pmatrix} x_0 \\ \Theta_x^* \\ y_0 \\ \Theta_y^* \end{pmatrix}$$

x_0, y_0 : Position at Interaction Point
 Θ_x^*, Θ_y^* : Scattering Angle at IP
 x_D, y_D : Position at Detector
 Θ_D^x, Θ_D^y : Angle at Detector

MEASUREMENT TECHNIQUE

To a good approximation the magnet transport equations that connect the initial scattering angle θ_y^* of the scattered proton in the vertical direction and the initial interaction position y_0 to the measured position y and angle θ_y at the detector are :

$$\begin{aligned} y &= a_{11} \cdot y_0 + L_{eff}^y \cdot \theta_y^* \\ \theta_y &= a_{12} \cdot y_0 + a_{22} \cdot \theta_y^* \end{aligned}$$

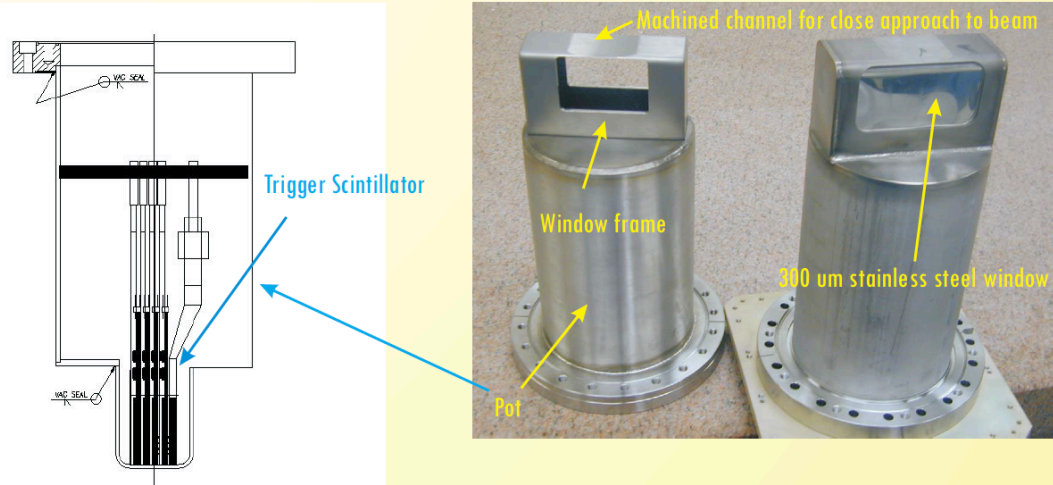
where a_{ij} and $L_{eff}^y \equiv a_{21}$ are coefficients of the beam transport matrix. The position of the two Roman pots closest to the IR were chosen such that a_{11} is small and L_{eff}^y is large, so that:

$$y \approx L_{eff}^y \cdot \theta_y^* \quad \text{Parallel to point focusing}$$

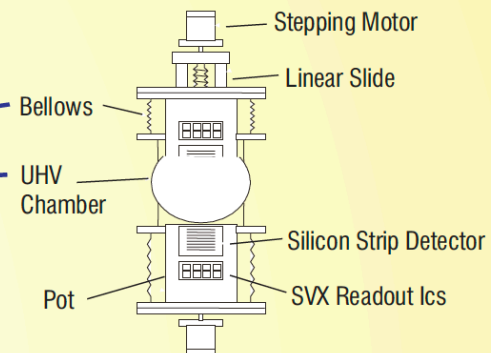
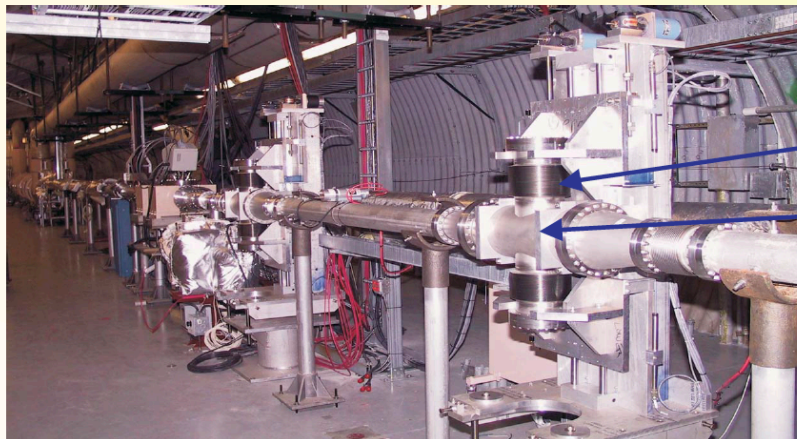
The hit position depends only on the scattering angle (parallel to point focusing). The large L_{eff}^y maximizes low $|t|$ acceptance.

Roman Pot Design – Very Conservative

Roman Pot Design

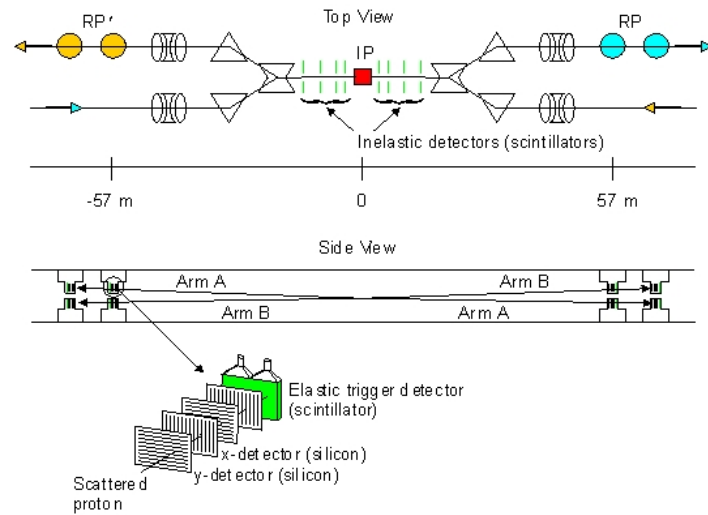


Roman Pot Stations



Roman Pot Detector System

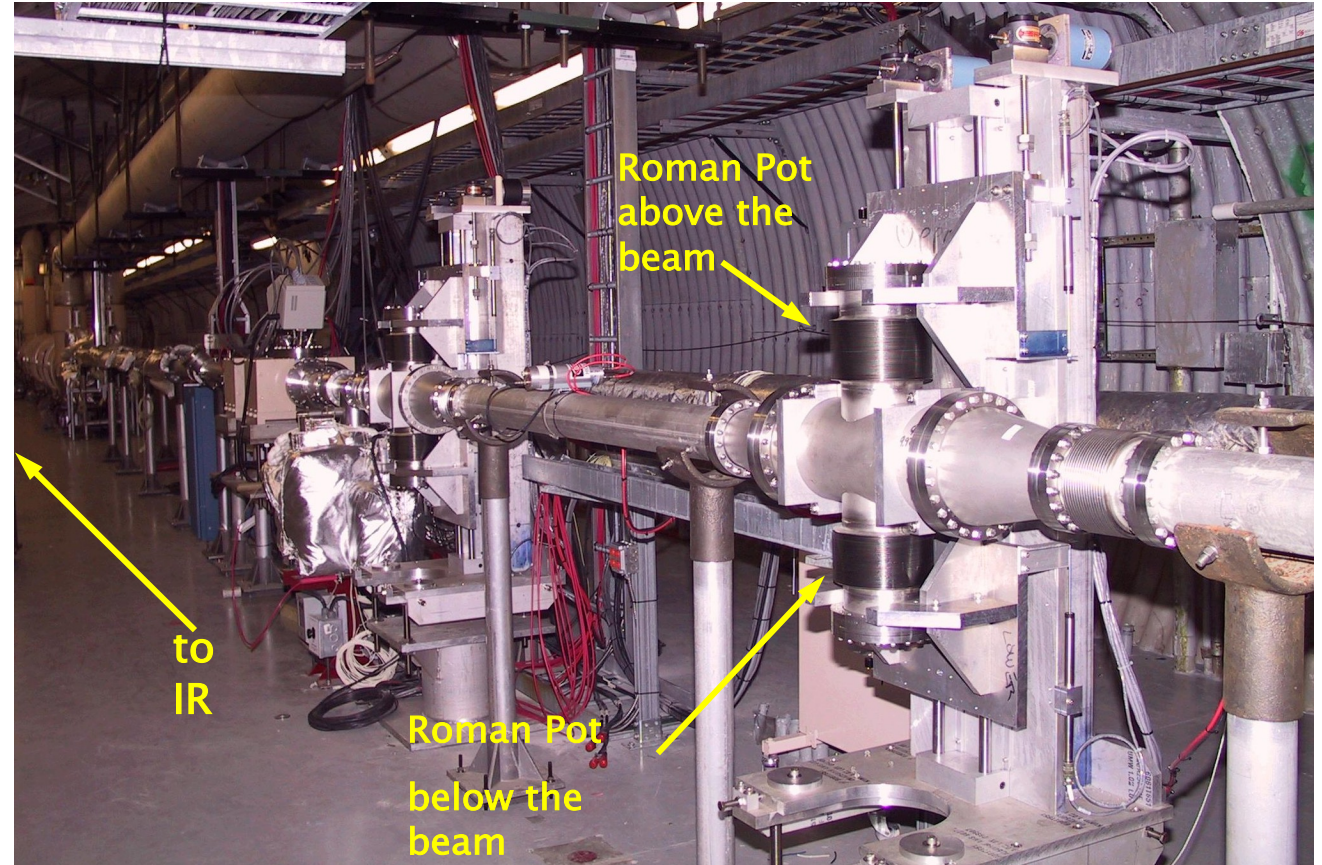
The Setup



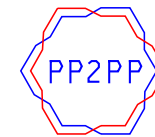
$$\vec{p}_1 = -\vec{p}_2 \Rightarrow (\Theta_x^1, \Theta_y^1) = (-\Theta_x^2, -\Theta_y^2)$$

In elastic scattering protons are acollinear.

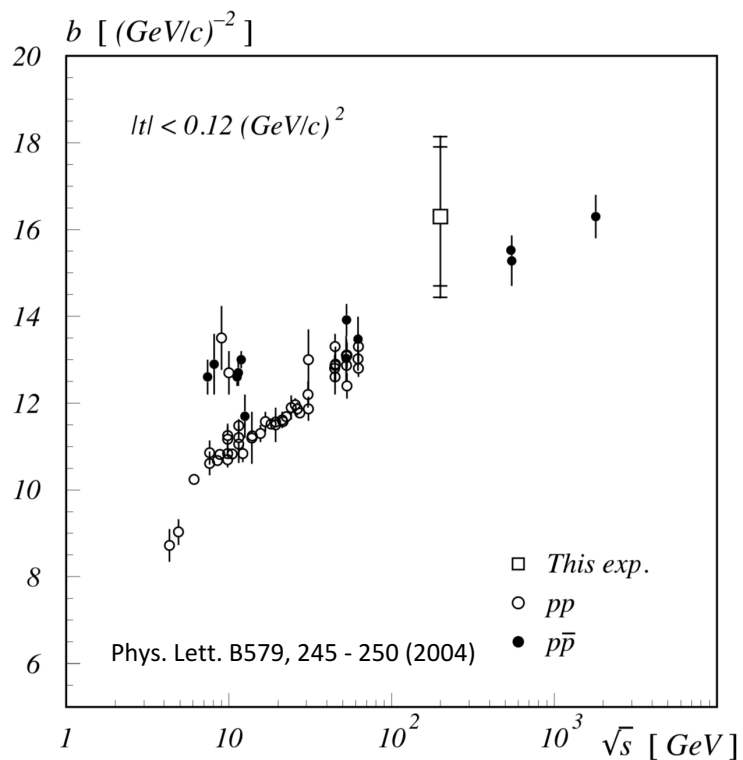
Very important constraint in the analysis



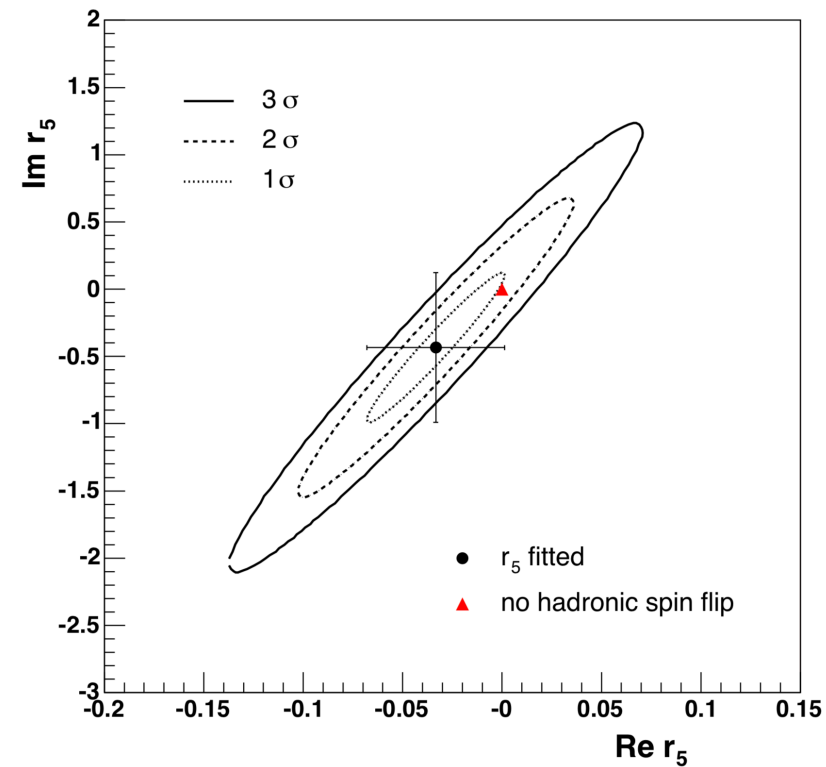
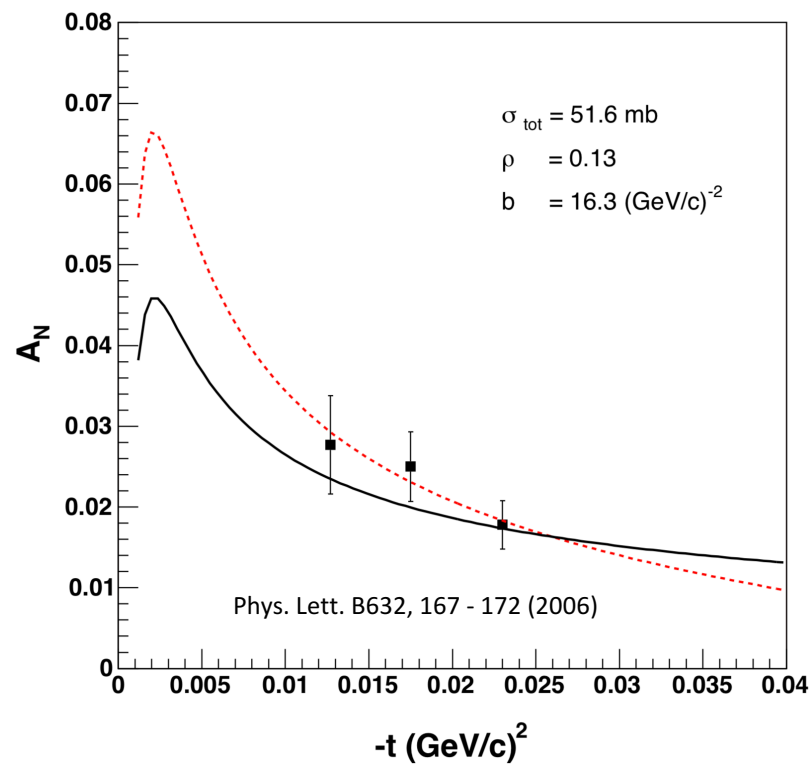
Results from PP2PP



B- Slope



Single spin asymmetry A_N



Results from PP2PP

TABLE I: Double spin asymmetries A_{NN} , A_{SS} , $(A_{NN} + A_{SS})/2$ and $(A_{NN} - A_{SS})/2$ for the t -interval $0.010 \leq -t \leq 0.030$ (GeV/c)² at $\langle -t \rangle = 0.0185$ (GeV/c)².

	A_{NN}	A_{SS}	$(A_{NN} + A_{SS})/2$	$(A_{NN} - A_{SS})/2$
$Asym$	0.0298	0.0035	0.0167	0.0131
$\Delta Asym$ (stat.+norm.)	± 0.0166	± 0.0081	± 0.0091	± 0.0096
$\Delta Asym$ (syst.)	± 0.0045	± 0.0031	± 0.0034	± 0.0072
$\Delta Asym$ due to $\Delta(P_Y \cdot P_B)$	± 32.3 %			

Phys. Lett. B647, 98 - 103 (2007)

Then the 2006 RHIC funding crisis came

In 2005, despite very good progress and three publications being worked on, the PP2PP experiment was cancelled by the BNL ALD.

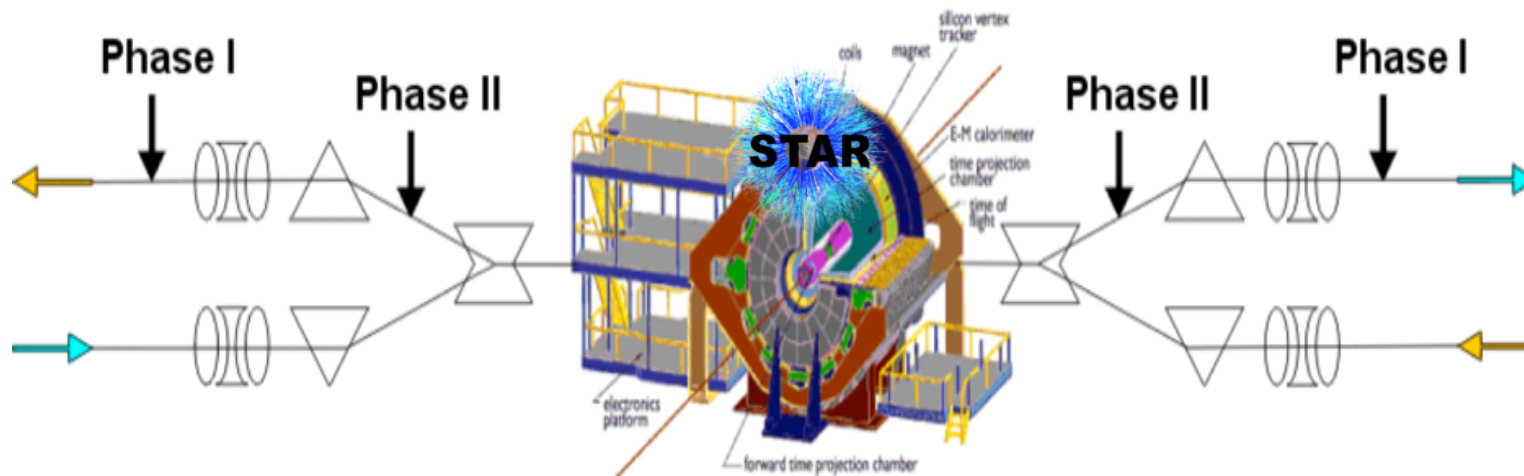


This is when I learned the importance of this cartoon.

Joining STAR in 2006: Physics with Tagged Forward Protons

Need detectors to tag forward protons and detector with good acceptance and particle ID to measure central system

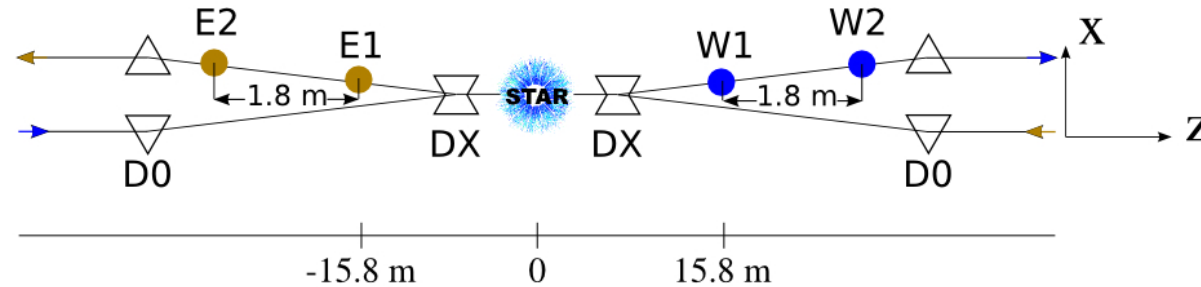
Roman Pots of PP2PP and STAR



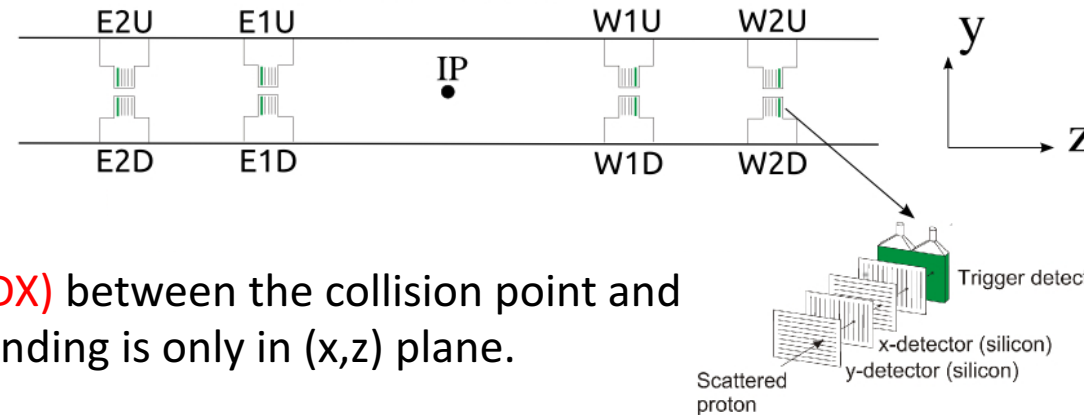
1. Elastic Scattering
2. Central Exclusive Production
3. Particle Production in SDD

Phase II Experimental Setup

Top view



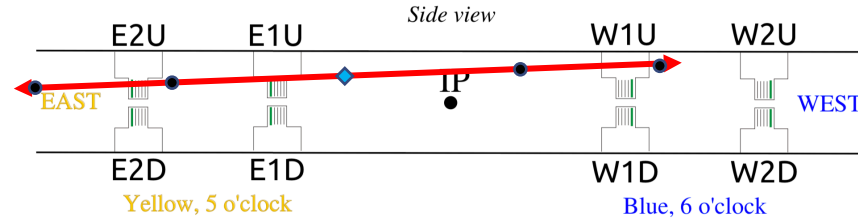
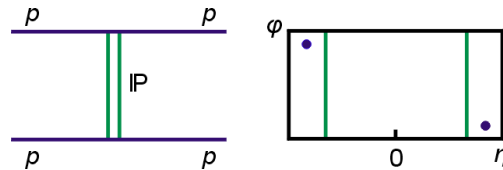
Side view



There is only one dipole magnet (DX) between the collision point and the Roman Pots (RPs). Bending is only in (x,z) plane.

In this configuration, RP program at STAR was able to acquire large data samples without special running conditions – mostly for CEP, SDD and CP analyses.

Results: Elastic Scattering



$$\frac{d\sigma_{el}}{dt} = \frac{1 + \rho^2}{16\pi(\hbar c)^2} \cdot \sigma_{tot}^2 \cdot e^{-B|t|}$$

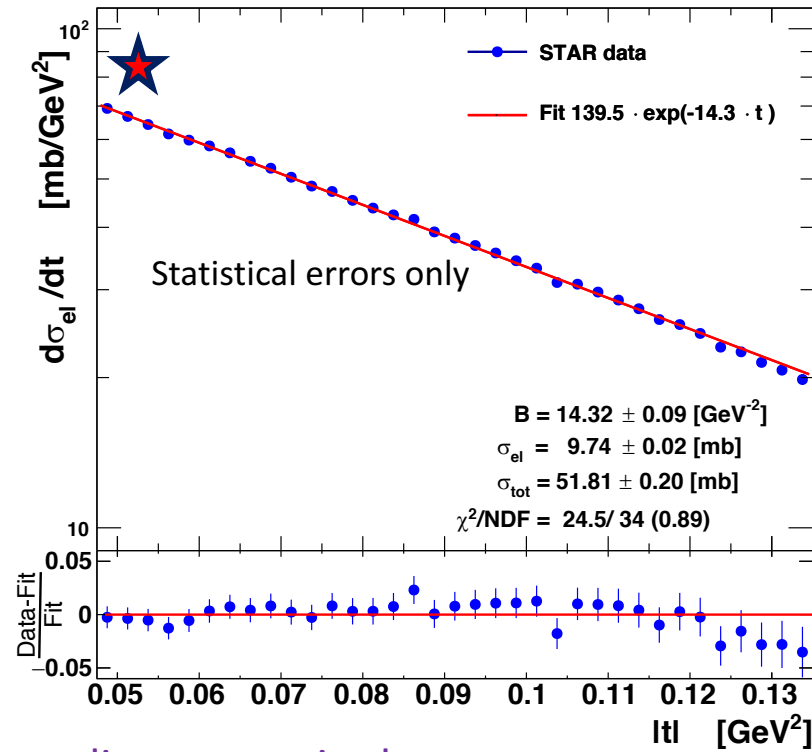
Optical theorem

$$\sigma_{tot}^2 = \left(\frac{16\pi(\hbar c)^2}{1 + \rho^2} \right) \left. \frac{d\sigma_{el}}{dt} \right|_{t=0}$$

Extrapolated to full t-range

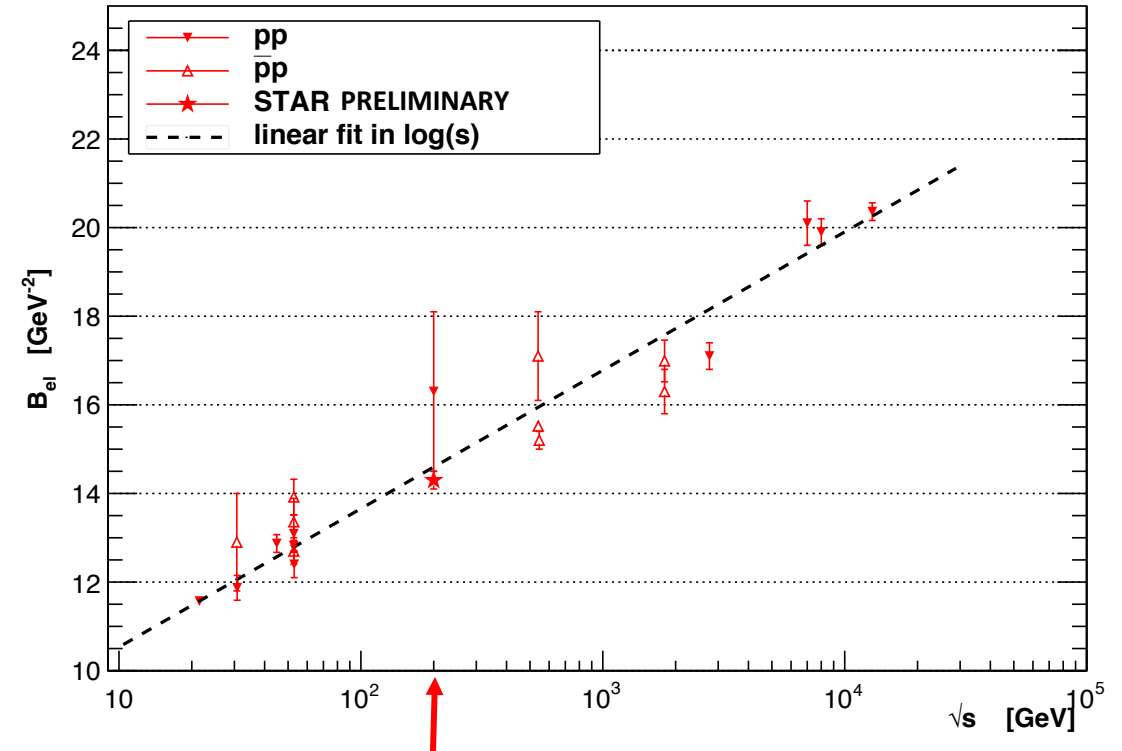
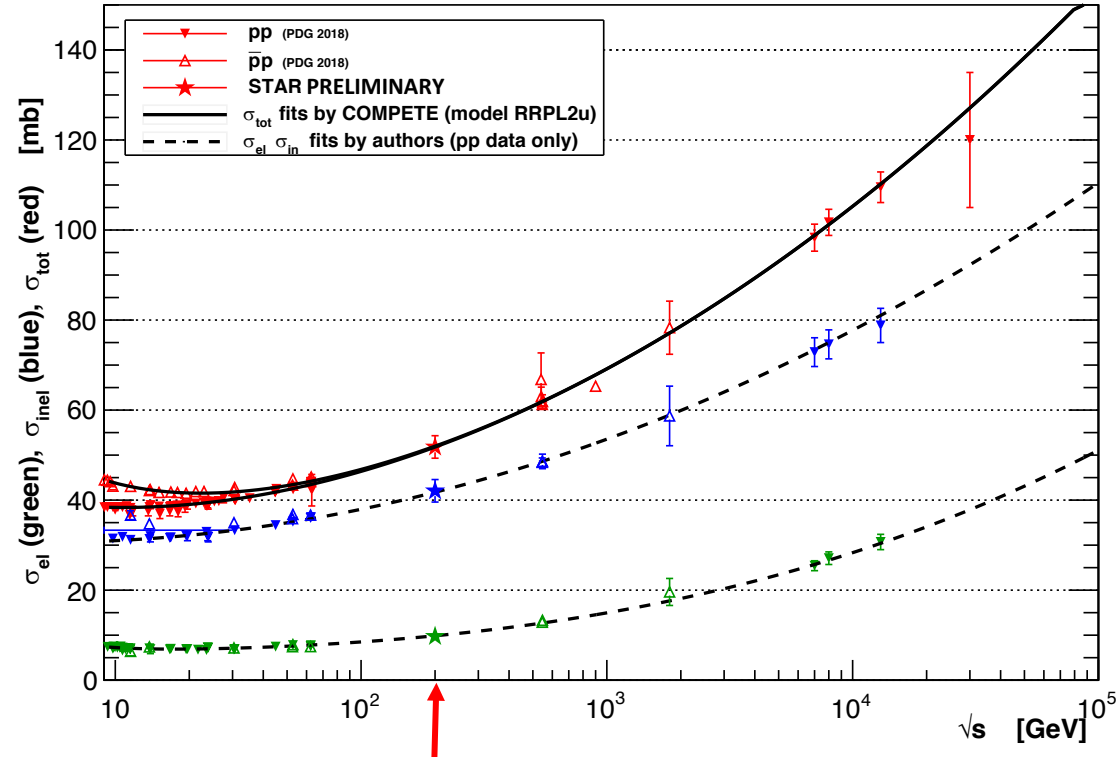
$$\sigma_{el} = \int \frac{d\sigma_{el}}{dt} dt$$

The value of $\rho = 0.128$ from COMPETE model was used*.
 * Phys. Rev. Lett. 89 (2002) 201801



We don't see a need for a nonlinear term in the exponent

Comparison with the World Data



STAR results compare well with the world data and the COMPETE predictions: Phys. Rev. Lett. 89 (2002) 201801

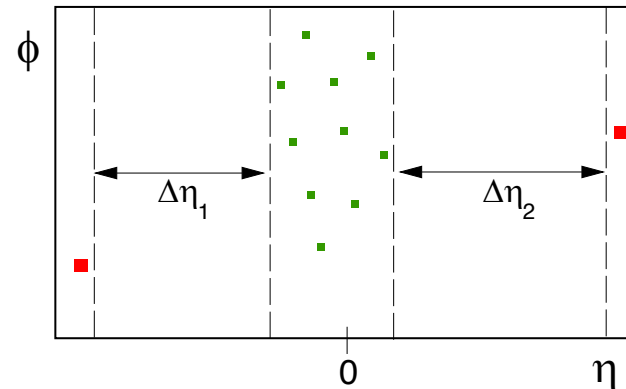
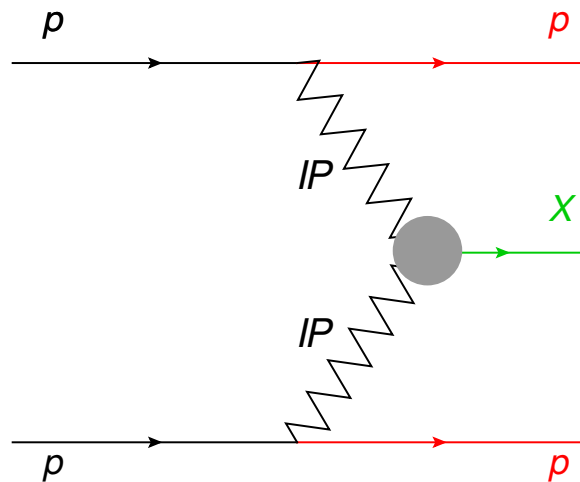
Plots from the TOTEM Collaboration <https://arxiv.org/pdf/1712.06153v2.pdf> with STAR preliminary results added

Central Exclusive Production (CEP)



Exclusive means that all particles in the final state are measured

$$pp \Rightarrow p X p$$



For each proton vertex one has

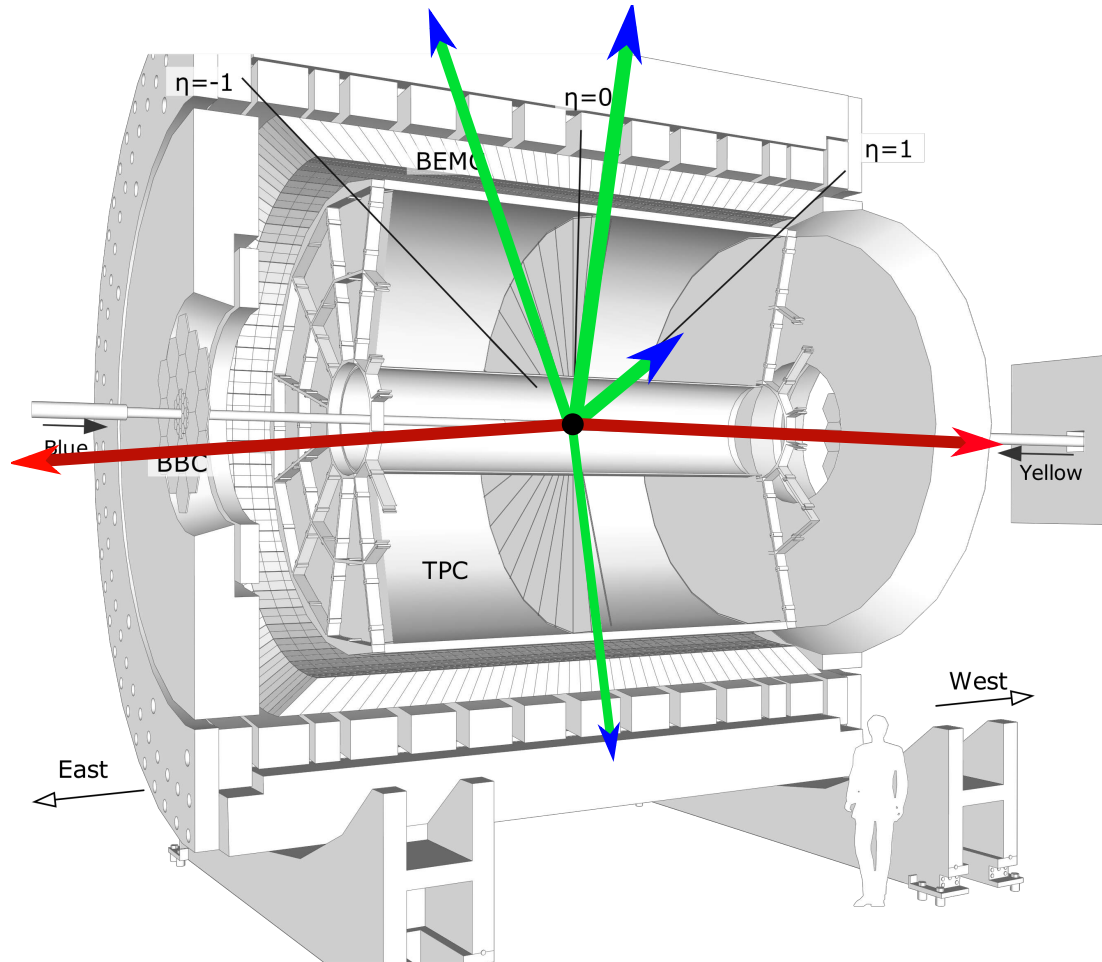
t four-momentum transfer

$$\xi = \Delta p/p$$

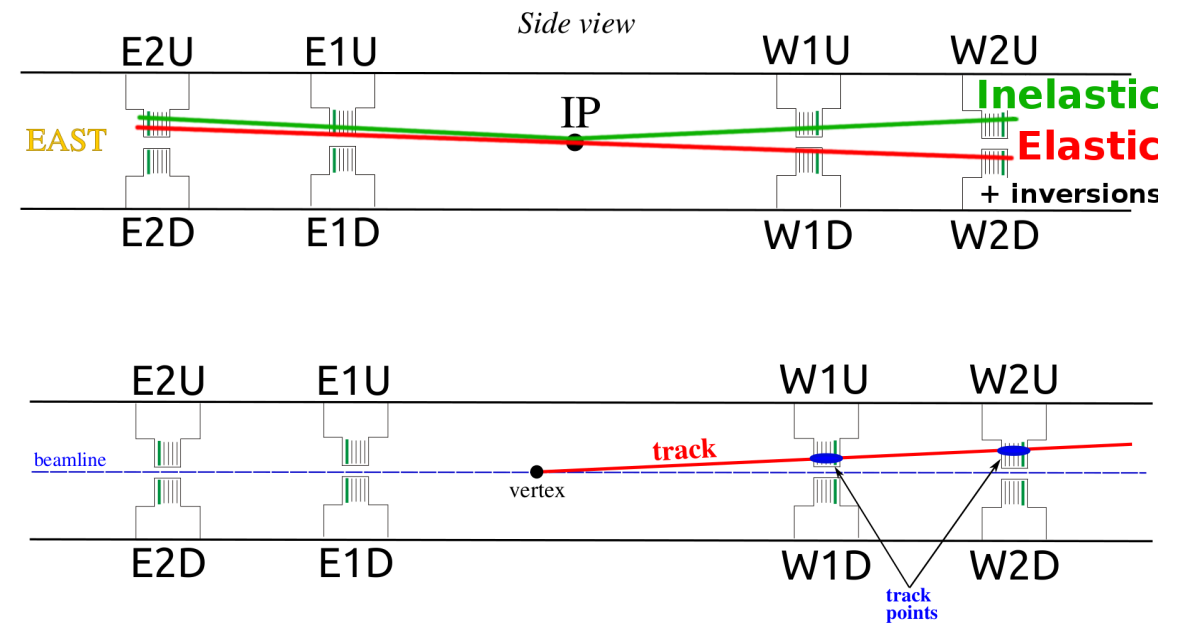
M_X invariant mass

In terms of QCD, Pomeron exchange consists of the exchange of a color singlet combination of gluons. Hence, triggering on forward protons at high (RHIC) energies predominantly selects exchanges mediated by gluonic matter.

CEP at STAR



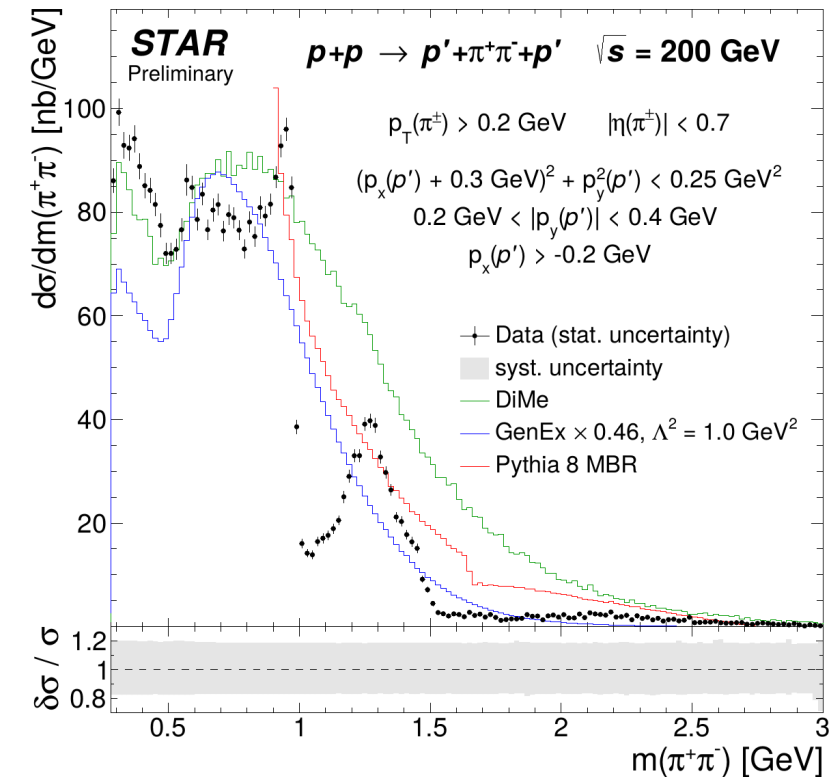
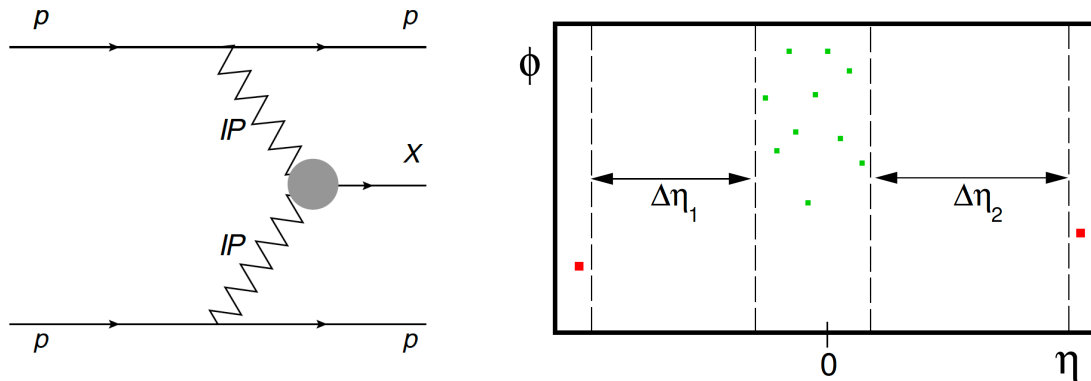
Roman Pots



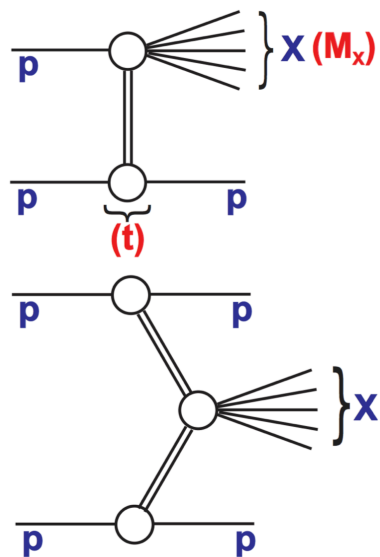
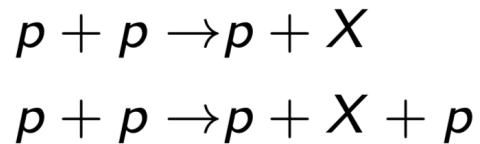
Central Exclusive Production



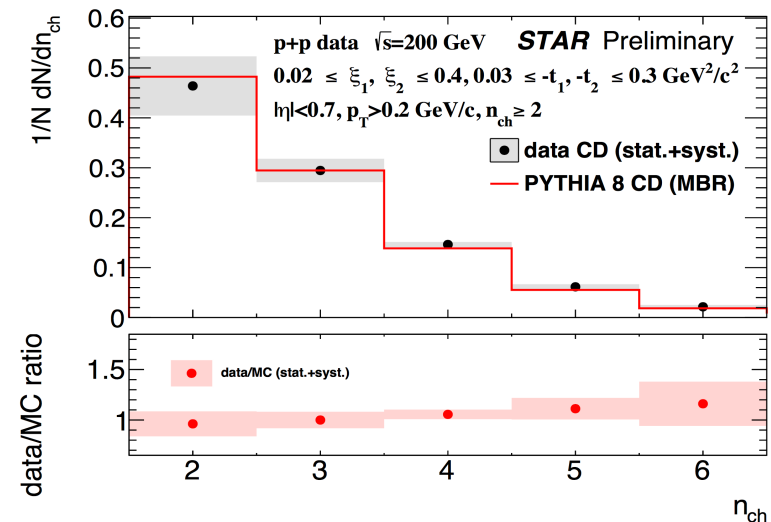
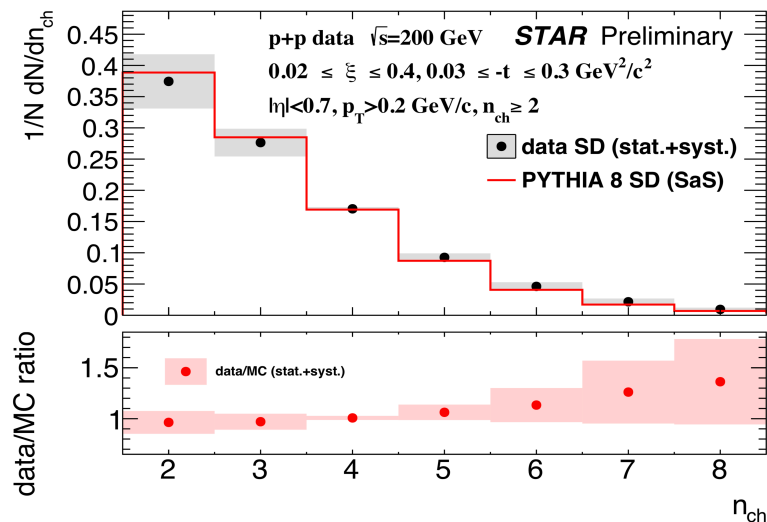
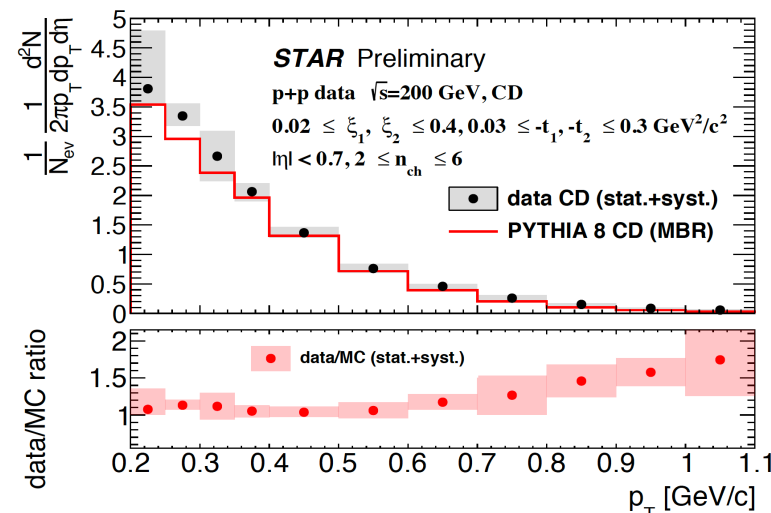
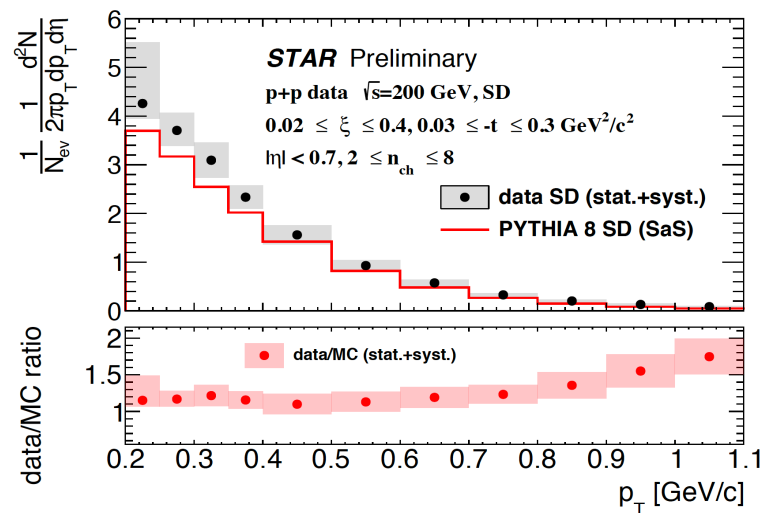
Results on production and measurement of low-mass central states in diffractive proton-proton interactions with **detection of forward protons**.



Charged Particle Production at Mid Rapidity in SDD and CP Processes



Fairly good agreement
between MC and data



Summary

1. Roman Pots at RHIC were used successfully in two experiments at RHIC: PP2PP and STAR
2. Many physics results were obtained and few more coming
3. Few lessons learned:
 - It is important to have Roman Pots integrated and optimized at the design stage of the experiments - not a problem for EIC since measuring of forward protons is essential for many physics topics.
 - Knowledge of magnetic elements with as run parameters is crucial for precision measurements.
 - Alignment with respect to the magnetic field and the beam trajectory is important and should be part of the plan from the beginning.
 - Survey of limiting apertures, especially in (x,y) plane.